

WARM BACKGROUND AND OVERVIEW

During the last century, population and economic growth have caused increased consumption of materials such as minerals, wood products and food. Materials consumption continues to accelerate while simultaneously shifting away from renewable materials like agriculture and forestry products toward non-renewable products such as metals and fossil fuel-derived products (EPA, 2009c). Source reduction, reuse and recycling of materials are ways that we can manage materials more sustainably.

Extracting, harvesting, processing, transporting and disposing of these materials result in greenhouse gas (GHG) emissions, in part due to the large amounts of energy required for these life-cycle stages. The U.S. Environmental Protection Agency's (EPA) Waste Reduction Model (WARM), the focus of this documentation, is a tool designed to help managers and policy-makers understand and compare the life-cycle GHG and energy implications of materials management options (recycling, source reduction, landfilling, combustion with energy recovery, and composting) for materials commonly found in the waste stream. By comparing a baseline scenario (e.g., landfilling) to an alternate scenario (e.g., recycling), WARM can assess the energy and GHG implications that would occur throughout the material life cycle.

1 MATERIALS MANAGEMENT CONTEXT

The United States and the international community are focusing increasingly on a life-cycle materials management paradigm that considers the environmental impacts of materials at all life-cycle stages. Recognition is growing that, since traditional environmental policies focus on controlling "end-of-pipe" emissions, they do not provide a means for systematically addressing environmental impacts associated with the movement of materials through the economy. While "end-of-pipe" policies are often effective in controlling direct pollution, they may result in some environmental impacts being overlooked or shifted from one area of the life cycle to another (EPA, 2009c).

The EPA Office of Solid Waste and Emergency Response found that 42 percent of U.S. 2006 GHG emissions were associated with the manufacturing, use and disposal of materials and products (EPA, 2009b). As a result, changing materials management patterns is an important strategy to help reduce or avoid GHG emissions. Reducing the amount of materials used to make products, extending product life spans, and maximizing recycling rates are examples of possible materials management strategies that can significantly reduce GHG emissions (EPA, 2009b).

Private and public entities globally are moving toward life-cycle materials management. For example, the Organisation for Economic Cooperation and Development (OECD) and the Kobe 3R Action Plan (a plan issued by the Group of Eight) have recommended that member countries pay increased attention to life-cycle approaches to material flows. Companies in the metals, cement, agribusiness, food and retail industries are also formulating approaches to increase efficiency and reduce environmental impacts by taking a life-cycle view of materials and processes (EPA, 2009c).

Materials management refers to how we manage material resources as they flow through the economy, from extraction or harvest of materials and food (e.g., mining, forestry, and agriculture), production and transport of goods, use and reuse of materials, and, if necessary, disposal. The EPA 2020 Vision Workgroup defines materials management as "an approach to serving human needs by using/reusing resources most productively and sustainably throughout their life cycles, generally minimizing the amount of materials involved and all the associated environmental impacts" (EPA, 2009c).

2 GENESIS AND APPLICATIONS OF WARM

2.1 HISTORY OF WARM DEVELOPMENT

Recognizing the potential for source reduction and recycling of municipal solid waste (MSW) to reduce GHG emissions, EPA included a source reduction and recycling initiative in the original 1994 U.S. *Climate Change Action Plan*. EPA set an emission reduction goal based on a preliminary analysis of the potential benefits of these activities. It was clear that a rigorous analysis would be needed to gauge more accurately the total GHG emission reductions achievable through source reduction and recycling.

That *all* of the options for managing MSW should be considered also became clear. By addressing a broader set of MSW management options, EPA could gain a more comprehensive picture of the GHG benefits of voluntary actions in the waste sector and assess the relative GHG impacts of various waste management approaches. To this end, EPA launched a major research effort, which resulted in the development of life-cycle GHG and energy factors for materials across several categories (e.g., plastics, metals, wood products), the online GHG and energy calculation tool WARM applying these factors, and accompanying documentation. The first documentation report, entitled *Greenhouse Gas Emissions from Management of Selected Materials in Municipal Solid Waste*, was published in 1998, the second edition in 2002 (retitled *Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks*) and the third edition in 2006 (EPA, 1998, 2002, 2006).

This new documentation effort, initiated in 2010, has reorganized the documentation into chapters by material and by process and includes more in-depth descriptions of the WARM emission factors. Whereas the previous documentation reports were structured only around process chapters (i.e., source reduction, recycling, composting, combustion, landfilling), this materials-based structure allows EPA to provide WARM users with more detailed information about the specific materials analyzed in WARM. This information was to a large extent omitted in previous versions of the report. As WARM has grown in popularity, many users have become more interested in the details of the calculations behind specific material emission factors, and EPA hopes that this new documentation effort will provide these users with more useful information.

This effort also included materials chapters on newly added construction and demolition (C&D) materials. The Roadmap to the New Documentation describes the revisions made since the last version of the report and includes information on updates made to the WARM versions since the third version of the report. The model itself has been updated on an annual basis to reflect updated statistics on national average electricity generation fuel mix, transmission and distribution losses, coal weighting for electricity generation, electricity generation per fuel type, the carbon content of fuels, landfill methane generation distribution (by type of landfill), landfill gas recovery and flaring rates, and waste generation and recovery rates. In addition, annual updates have often included new material emission factors and other improvements to the analysis (Exhibit 1, found in section 2.4, provides the dates when materials were added to WARM).

The latest recent versions of WARM have undergone some of the most extensive improvements and additions since the tool's inception. In WARM Version 11 (released in August 2010), new emission factors were added for six construction and demolition (C&D) materials: asphalt concrete, asphalt shingles, drywall, fiberglass insulation, vinyl flooring and wood flooring, and emission factors for tires were also updated. Additionally, the Excel version of WARM now incorporates region-specific electricity grid factors to more accurately model emissions associated with avoided generation of electricity due to landfill gas recovery in the landfilling pathway and waste-to-energy (WTE) in the combustion pathway.

The Excel version of WARM also includes an updated method for estimating landfill gas collection efficiency, allowing the user to select between three landfill gas collection efficiency scenarios based on specific landfill recovery characteristics: typical operation, worst-case collection and aggressive gas collection. Component-specific decay rates were added for all organic materials to more accurately model the rate at which each material decays within a landfill under given landfill moisture conditions. The component-specific decay rates modeled in WARM are also available as a user-defined input in the Excel version of WARM and are based on selecting one of four landfill climate/moisture characteristics: dry, average, wet or bioreactor. In WARM Version 12 (released in February 2012), new emission factors were added for four plastics, linear low-density polyethylene (LLDPE), polypropylene (PP), polystyrene (PS) and polyvinyl Chloride (PVC). Additionally, new emission factors were developed for polylactide (PLA) and aluminum ingot. Several other emission factors were revised: the emission factor for aluminum cans has been updated to include additional can manufacturing steps in the updated life cycle data as well as factor in industry-specific electricity grid mix assumptions; the combustion and open-loop recycling pathways for residential broadloom carpeting now incorporates updated data; and the emission factors for three plastics (high-density polyethylene (HDPE), low-density polyethylene (LDPE) and polyethylene terephthalate (PET)) were updated using new life-cycle data. The mixed recycling and mixed plastics recycling factors have both changed due to 1) revisions to the underlying numbers in the virgin and recycled HDPE and PET emission factors, 2) the removal of the LDPE recycling pathway, and 3) updates to the waste generation and recovery numbers based on EPA's "Municipal Solid Waste (MSW) in the United States: Facts and Figures" report.

2.2 WARM AUDIENCE AND RELATED EFFORTS

The primary application of WARM is to support materials-related decision-making in the context of climate change. By quantifying the climate impacts of materials management decisions, the factors in this report and the tool enable municipalities, companies and other waste- and program-management decision-makers to measure the benefits of their actions. Other EPA decision-support tools such as the Recycled Content Tool (ReCon), Individual WARM (iWARM), Saving Money and Reducing Trash Benefit Evaluation Tool (SMART BET), and the Office Carbon Footprint Tool, rely on WARM energy and emission factors to help users make a wide range of decisions. For example, SMART BET is designed to help local waste managers decide whether unit-based pricing for solid waste management (also known as Pay-As-You-Throw or PAYT) is the right model for their community. SMART BET calculates both cost savings and GHG savings associated with a possible PAYT model using user-defined inputs. The iWARM tool uses life-cycle information from WARM to quantify energy benefits of recycling small quantities of common waste materials by calculating the "run time" of a variety of household appliances (e.g., clothes washer, hairdryer, etc.) using electricity savings from recycling materials. Other applications have included quantifying the GHG reductions

Global Warming Potentials

CO₂, CH₄, N₂O and perfluorocarbons (PFCs) are very different gases in terms of their heat-trapping potential. The Intergovernmental Panel on Climate Change (IPCC) has established CO₂ as the reference gas for measurement of heat-trapping potential (also known as global warming potential or GWP). By definition, the GWP of one kilogram (kg) of CO₂ is one. The GWPs of other common GHGs from materials management activities are as follows:

- CH₄ has a GWP of 21, which means that one kg of CH₄ has the same heat-trapping potential as 21 kg of CO₂.
- N₂O has a GWP of 310.
- PFCs are the most potent GHG included in this analysis; GWPs are 6,500 for CF₄ and 9,200 for C₂F₆.

WARM expresses comparative GHG emissions in metric tons of CO₂ equivalents (MTCO₂E), which uses the tool of GWP to allow all emissions to be compared on equal terms.

WARM uses GWPs from IPCC (1996).

from voluntary programs aimed at source reduction and recycling, such as EPA's WasteWise and Pay-As-You-Throw programs.

The international community has shown considerable interest in using the emission factors—or adapted versions—to develop GHG emission estimates for non-U.S. materials management.¹ For example, Environment Canada and Natural Resources Canada employed EPA's life-cycle methodology and components of its analysis to develop a set of Canada-specific GHG emission factors to support analysis of waste-related mitigation opportunities (Environment Canada, 2005).

2.3 ESTIMATING AND COMPARING NET GHG EMISSIONS

WARM compares the emissions and offsets resulting from a material in a baseline and an alternative management pathway in order to provide decision-makers with comparative emission results. For example, WARM could be used to calculate the GHG implications of landfilling 10 tons of office paper versus recycling the same amount of office paper.

The general formula for net GHG emissions for each scenario modeled in WARM is as follows:

$$\text{Net GHG emissions} = \text{Gross manufacturing GHG emissions} - (\text{Increase in carbon stocks} + \text{Avoided utility GHG emissions})$$

This equation should only be considered in the context of comparing two alternative materials management scenarios in order to identify the lowest net GHG emissions. The following circumstances influence the net GHG emissions of a material:

- Through *source reduction* (for example, “lightweighting” a beverage can—using less aluminum for the same function), GHG emissions throughout the life cycle are avoided. In addition, when paper products are source reduced, additional carbon is sequestered in forests, through reduced tree harvesting.
- Through *recycling*, the GHG emissions from making an equivalent amount of material from virgin inputs are avoided. In most cases, recycling reduces GHG emissions because manufacturing a product from recycled inputs requires less energy than making the product from virgin inputs.
- *Composting* with application of compost to soils results in carbon storage.
- *Landfilling* results in both CH₄ emissions from biodegradation and biogenic carbon storage. If captured, the CH₄ may be flared, which simply reduces CH₄ emissions (since the CO₂ produced by flaring is biogenic in origin, it is not accounted for in this assessment of anthropogenic emissions). If captured CH₄ is burned to produce energy, it offsets emissions from fossil fuel consumption.
- *Combustion* of waste may result in an electricity utility emissions offset if the waste is burned in a waste-to-energy facility, which displaces fossil-fuel-derived electricity.

2.4 MATERIALS CONSIDERED IN WARM

To measure the GHG impacts of materials management, EPA first decided which materials and products to analyze. EPA surveyed the universe of materials and products found in the solid waste stream and identified those that are most likely to have the greatest impact on GHGs. These

¹ Note that waste composition and product life cycles vary significantly among countries. This report may assist other countries by providing a methodological framework and benchmark data for developing GHG emission estimates for their solid waste streams.

determinations were initially based on (1) the quantity generated; (2) the differences in energy use for manufacturing a product from virgin versus recycled inputs; and (3) the potential contribution of materials to CH₄ generation in landfills. Since the initial assessment, many materials have been added. Materials that EPA selects for inclusion in WARM are generally selected based on the three principles above, with the additional criterion that enough data be available to create defensible emission factors. As of February 2012 in which WARM Version 12 was released, WARM included 46 materials, products and mixed categories, as listed in Exhibit 1 by category type. Exhibit 1 also shows the main sources of virgin and recycled production energy data for each material, the vintage of those data, the year each material was first added to WARM, the percentage each material constitutes of total MSW generated in the United States (to the extent information is available), and whether the recycling process is modeled as open- or closed-loop in WARM (more information on the recycling process is presented in the [Recycling](#) chapter). EPA is in the process of gathering and reviewing new life-cycle inventory (LCI) data for several material types to develop updated and new emission factors for WARM.

Exhibit 1: Current Materials and Products in WARM, Historical Inclusion, and Source of Data

| Material/Product | Year First Added to WARM (updated year if applicable) | Source of Main Process Energy Data | Approximate Year(s) of Current Energy Data ^a | % of MSW Generation by Weight ^b | Open- or Closed-Loop Recycling? ^c |
|----------------------------------|---|--|---|--|--|
| Metals and Glass | | | | | |
| Aluminum Cans | 1998 (2012) | PE Americas (2010) | 2006 | 0.6% | Closed |
| Aluminum Ingot | 2012 | PE Americas (2010) | 2006 | NE | Closed |
| Steel Cans | 1998 | FAL (1998b) | 1990 | 1.0% | Closed |
| Copper Wire | 2005 | Battelle (1975); Kusik and Kenahan (1978); FAL (2002b) | 1973–2000 | NE | Open |
| Glass | 1998 | RTI (2004) | Late 1990s | 4.5% | Closed |
| Plastics | | | | | |
| HDPE (high-density polyethylene) | 1998 (2012) | FAL (2011) | 2000s | 1.6% | Closed |
| LDPE (low-density polyethylene) | 1998 (2012) | FAL (2011) | 2000s | 1.2% | Closed |
| PET (polyethylene terephthalate) | 1998 (2012) | FAL (2011) | 2000s | 1.2% | Closed |
| LLDPE | 2012 | FAL (2011) | 2000s | NE | Closed |
| PP | 2012 | FAL (2011) | 2000s | NE | Closed |
| PS | 2012 | FAL (2011) | 2000s | NE | Closed |
| PVC | 2012 | FAL (2011) | 2000s | NE | Closed |
| Paper and Wood | | | | | |
| Corrugated Containers | 1998 | RTI (2004) | Late 1990s | 12.3% | Both |
| Magazines/Third-Class Mail | 2001 | RTI (2004) | Late 1990s | 3.3% | Closed |
| Newspaper | 1998 | RTI (2004) | Late 1990s | 4.3% | Closed |
| Office Paper | 1998 | RTI (2004) | Late 1990s | 2.4% | Closed |
| Phone Books | 2001 | RTI (2004) | Late 1990s | 0.3% | Closed |
| Textbooks | 2001 | RTI (2004) | Late 1990s | 0.5% | Closed |
| Dimensional Lumber | 1998 | FAL (1998c) | Mid 1990s | 3.4% | Closed |
| Medium-Density Fiberboard | 1998 | FAL (1998c) | Mid 1990s | NE | Closed |
| Organics | | | | | |
| Food Scraps | 1998 | NA | NA | 12.5% | NA |
| Yard Trimmings | 1998 | NA | NA | 12.8% | NA |
| Grass | 2001 | NA | NA | NE | NA |
| Leaves | 2001 | NA | NA | NE | NA |
| Branches | 2001 | NA | NA | NE | NA |

| | | | | | |
|--|-------------|---|--|-------|--------|
| PLA | 2012 | NatureWorks, LLC (2010) | 2009 | NE | NA |
| Mixed Categories | | | | | |
| Mixed Paper (general) | 1998 | Virgin: FAL (1998a), RPTA (2003) Recycled: RPTA (2003) | Virgin: 1996; Recycled: early 2000s | NE | Open |
| Mixed Paper (primarily residential) | 1998 | FAL (1998a) | 1996 | NE | Open |
| Mixed Paper (primarily from offices) | 1998 | FAL (1998a) | 1996 | NE | Open |
| Mixed Metals | 2002 | NA | NA | 4.3% | NA |
| Mixed Plastics | 2001 | NA | NA | 10.9% | NA |
| Mixed Recyclables | 1998 | NA | NA | NE | NA |
| Mixed Organics | 2001 | NA | NA | NE | NA |
| Mixed MSW | 2001 | NA | NA | NE | NA |
| Composite Products | | | | | |
| Carpet ^d | 2004 (2012) | FAL (2002a); Realff (2011) | 2000s | 1.2% | Open |
| Personal Computers ^d | 2004 | FAL (1998b) | 1973–2001 | 0.3% | Open |
| Construction and Demolition (C&D) | | | | | |
| Clay Bricks | 2004 | Athena Sustainable Materials Institute (1998) | Mid-late 1990s | NA | NA |
| Concrete ^d | 2004 | U.S. Census Bureau (1997), Wilburn and Goonan (1998) | 1997 | NA | Open |
| Fly Ash | 2004 | IPCC (1996), PCA (2003), Nisbet et al. (2000) | Early 2000s | NA | Open |
| Tires ^d | 2006 | Athena Sustainable Materials Institute (2000), Atech Group (2001), EIA (2009), Corti and Lombardi (2004) | Early 2000s | 1.9% | Open |
| Asphalt Concrete ^d | 2010 | U.S. Census Bureau (1997), Athena Sustainable Materials Institute (2001), U.S. Census Bureau (2001), Environment Canada (2005), Levis (2008), NREL (2009) | Early 2000s | NA | Closed |
| Asphalt Shingles ^d | 2010 | Athena Sustainable Materials Institute (2000), Cochran (2006), CMRA (2007) | Early 1990s | NA | Open |

| | | | | | |
|-----------------------------|------|---|---------------------------------|----|------|
| Drywall ^d | 2010 | Venta (1997); recycling data from WRAP (2008) | Virgin: 1997; Recycled: 2008 | NA | Both |
| Fiberglass Insulation | 2010 | Lippiatt (2007), Enviros Consulting (2003) for glass cullet production | Mid 2000s | NA | NA |
| Vinyl Flooring ^d | 2010 | ECOBILAN (2001), FAL (2007), Lippiatt (2007), Ecoinvent Centre (2008) | 2007 | NA | NA |
| Wood Flooring ^e | 2010 | Bergman and Bowe (2008), Hubbard and Bowe (2008), Bergman (2010) | Late 2000s | NA | NA |

NA = Not applicable.

NE = Not estimated.

^a Note that years are approximate because each source draws on a variety of data sources from different years.

^b Source for percent generation data is EPA (2008).

^c Closed-loop recycling indicates a recycling process where end-of-life products are recycled into the same product. Open-loop recycling indicates that the products of the recycling process (secondary product) are not the same as the inputs (primary material).

^d Indicates composite product.

^e Wood flooring also falls under the Paper and Wood category.

There are generally two overarching waste categories under which material types listed in Exhibit 1 fall. Municipal solid waste generally includes metals and glass, plastics, paper and wood, organics, mixed categories and composite products. These materials are household, commercial, institutional and light industrial waste collected and managed by a municipality. The construction and demolition materials are materials that are produced during construction, renovation or demolition of structures and include clay bricks, concrete, fly ash, tires, asphalt concrete, asphalt shingles, drywall, fiberglass insulation, vinyl flooring and wood flooring. EPA's interest in C&D materials is the result of a growing interest in environmentally friendly or "green" building practices, including reusing and recycling the impressive quantities of C&D debris that are generated each year. In 2008, 143.5 million tons of C&D waste were generated (Waste Business Journal, 2009). One major difference between waste management for C&D materials versus MSW materials is that C&D materials are typically disposed of in landfills created specifically for C&D waste that do not accept MSW waste. C&D and MSW landfills differ in several ways, including in the design and operation requirements of the landfills. From the GHG perspective, the most significant difference between the two landfill types is that C&D landfills generally do not have the landfill methane capture systems that are common at MSW landfills. Thus, the methane that is produced in C&D landfills is eventually released directly to the atmosphere.

The MSW materials listed in Exhibit 1 constitute more than 65 percent, by weight, of MSW, as shown in the fifth column of Exhibit 1. Several materials, including most C&D materials, were not included in the waste characterization report cited here, so the utility of this percent estimate is limited.² The definitions of the each of the WARM materials included in Exhibit 1 are summarized below in Exhibit 2.

² Note that these data are based on national averages. The composition of solid waste varies locally and regionally.

Exhibit 2: WARM Material Definitions

| WARM Material | WARM Data Source Definition |
|----------------------------|---|
| Aluminum Cans | Aluminum cans represent cans produced out of sheet-rolled aluminum ingot. |
| Aluminum Ingot | Aluminum ingot is processed from molten aluminum in the form of a sheet ingot suitable for rolling, extruding, or shape casting. Thus, it serves as a pre-cursor to manufacture of aluminum products such as aluminum cans. It can serve as a proxy for certain aluminum materials such as electrical transmission and distribution wires, other electrical conductors, some extruded aluminum products, aluminum product cuttings, joinings and weldings, and consumer durable products such as home appliances, computers, and electronics. |
| Steel Cans | Steel cans represent three-piece welded cans produced from sheet steel that is made in a blast furnace and basic oxygen furnace (for virgin cans) or electric arc furnace (for recycled cans). |
| Copper Wire | Copper wire is used in various applications, including power transmission and generation lines, building wiring, telecommunication, and electrical and electronic products. |
| Glass | Glass represents glass containers (e.g., soft drink bottles and wine bottles). |
| HDPE | HDPE (high-density polyethylene) is usually labeled plastic code #2 on the bottom of the container, and refers to a plastic often used to make bottles for milk, juice, water and laundry products. It is also used to make plastic grocery bags. |
| LDPE | LDPE (Low-density polyethylene), usually labeled plastic code #4, is often used to manufacture plastic dry cleaning bags. LDPE is also used to manufacture some flexible lids and bottles. |
| PET | PET (Polyethylene terephthalate) is typically labeled plastic code #1 on the bottom of the container. PET is often used for soft drink and disposable water bottles, but can also include other containers or packaging. |
| LLDPE | LLDPE (linear low-density polyethylene) is used in high-strength film applications. Compared to LDPE, LLDPE's chemical structure contains branches that are much straighter and closely aligned, providing it with a higher tensile strength and making it more resistant to puncturing or shearing |
| PP | PP (Polypropylene) is used in packaging, automotive parts, or made into synthetic fibres. It can be extruded for use in pipe, conduit, wire, and cable applications. PP's advantages are a high impact strength, high softening point, low density, and resistance to scratching and stress cracking. A drawback is its brittleness at low temperatures |
| PS | GPPS (General Purpose Polystyrene) has applications in a range of products, primarily domestic appliances, construction, electronics, toys, and food packaging such as containers, produce baskets, and fast food containers. |
| PVC | PVC (Polyvinyl Chloride) is produced as both rigid and flexible resins. Rigid PVC is used for pipe, conduit, and roofing tiles, whereas flexible PVC has applications in wire and cable coating, flooring, coated fabrics, and shower curtains |
| PLA | Polylactic acid or PLA is a thermoplastic biopolymer constructed entirely from annually renewable agricultural products, e.g., corn, and used in manufacturing fresh food packaging and food service ware such as rigid packaging, food containers, disposable plastic cups, cutlery, and plates |
| Corrugated Containers | Corrugated container boxes made from containerboard (liner and corrugating medium) used in packaging applications. |
| Magazines/Third-Class Mail | Third Class Mail is now called Standard Mail by the U.S. Postal Service and includes catalogs and other direct bulk mailings such as magazines, which are made of coated, shiny paper. This category represents coated paper produced from mechanical pulp. |
| Newspaper | Newspaper represents uncoated paper made from 70% mechanical pulp and 30% chemical pulp. For the carbon sequestration portion of the factor, it was assumed that the paper was all mechanical pulp. |
| Office Paper | Office paper represents paper made from uncoated bleached chemical pulp. |
| Phone Books | Phone books represent telephone books that are made from paper produced from mechanical pulp. |
| Textbooks | Textbooks represent books made from paper produced from chemical pulp. |
| Dimensional Lumber | Lumber includes wood used for containers, packaging, and building and includes crates, pallets, furniture and dimensional lumber like two-by-fours. |
| Medium-Density Fiberboard | Fiberboard is a panel product that consists of wood chips pressed and bonded with a resin. Fiberboard is used primarily to make furniture. |
| Food Discards | Food consists of uneaten food and wasted prepared food from residences, commercial establishments such as grocery stores and restaurants, institutional sources such as school |

| | | |
|-----------------------|------------------------|---|
| | | cafeterias, and industrial sources such as factory lunchrooms. |
| Yard Trimmings | | Yard trimmings are assumed to be 50% grass, 25% leaves, and 25% tree and brush trimmings (EPA, 2008, p. 58) from residential, institutional and commercial sources. |
| Mixed Paper | General Definition | Mixed paper is assumed to be 24% newspaper, 48% corrugated cardboard, 8% magazines, and 20% office paper (Barlaz, 1998). |
| | Residential Definition | Residential mixed paper is assumed to be 23% newspaper, 53% corrugated cardboard, 10% magazines and 14% office paper (Barlaz, 1998). |
| | Office Definition | Office mixed paper is assumed to be 21% newspaper, 5% corrugated cardboard, 36% magazines and 38% office paper (Barlaz, 1998). |
| Carpet | | Carpet represents nylon broadloom residential carpet containing face fiber, primary and secondary backing, and latex used for attaching the backings. |
| Personal Computers | | PCs are made up of a central processing unit (CPU) and a cathode ray tube (CRT) monitor. The components of the CPU and monitor include steel housing, internal electric components, the CRT, plastic casing and circuit boards. In addition to these valuable components, PCs contain lead, brominated flame retardants and other potentially hazardous chemicals. |
| Clay Bricks | | Bricks are produced by firing materials such as clay, kaolin, fire clay, bentonite, or common clay and shale. The majority of the bricks produced in the United States are clay. In WARM, clay brick source reduction is considered to be the reuse of full bricks rather than the grinding and reusing of broken or damaged brick. |
| Concrete | | Concrete is a high-volume building material produced by mixing cement, water, and coarse and fine aggregates. In WARM, concrete is assumed to be recycled into aggregate, so the GHG benefits are associated with the avoided emissions from mining and processing aggregate. |
| Fly Ash | | Fly ash is a byproduct of coal combustion that is used as a cement replacement in concrete. |
| Tires | | Scrap tires are tires that have been disposed of by consumers and have several end uses in the U.S. market, including as a fuel, in civil engineering, and in various ground rubber applications such as running tracks and molded products. |
| Mixed Metals | | Mixed metals are made up of a weighted average of aluminum cans and steel cans. The exact percentage of each is updated annually based on EPA's report, <i>Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures</i> . |
| Mixed Plastics | | Mixed plastics are made up of a weighted average of HDPE, LDPE and PET plastic. The exact percentage of each is updated annually based on EPA's report, <i>Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures</i> . |
| Mixed Recyclables | | Mixed recyclables are made up of a weighted average of aluminum cans, steel cans, glass, HDPE, LDPE, PET, corrugated cardboard, magazines/third-class mail, newspaper, office papers, phone books, textbooks and dimensional lumber. The exact percentage of each is updated annually based on EPA's report, <i>Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures</i> . |
| Mixed Organics | | Mixed organics are made up of a weighted average based on 48% food scraps and 52% yard trimmings. See those definitions for details. The exact percentage of each is updated annually based on EPA's report, <i>Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures</i> . |
| Mixed MSW | | Mixed MSW (municipal solid waste) comprises the waste materials typically discarded by households and collected by curbside collection vehicles; it does not include white goods (e.g., refrigerators, toasters) or industrial waste. |
| Asphalt Concrete | | Asphalt concrete is composed primarily of aggregate, which consists of hard, graduated fragments of sand, gravel, crushed stone, slag, rock dust or powder. |
| Asphalt Shingles | | Asphalt shingles are typically made of a felt mat saturated with asphalt. Fiberglass shingles are composed of asphalt cement (22% by weight), a mineral stabilizer like limestone or dolomite (25%), and sand-sized mineral granules/aggregate (38%), in addition to the fiberglass felt backing (15%) (CMRA, 2007). |
| Drywall | | Drywall, also known as wallboard, gypsum board or plaster board, is manufactured from gypsum plaster and a paper covering. |
| Fiberglass Insulation | | Fiberglass insulation is produced from a blend of sand, limestone, soda ash and recycled glass cullet, which accounts for about 40% of the raw material inputs. |
| Vinyl Flooring | | All vinyl flooring is composed of polyvinyl chloride (PVC) resin, along with additives such as plasticizers, stabilizers, pigments and fillers. |

| | |
|---------------|--|
| Wood Flooring | Virgin hardwood flooring is produced from lumber. Coatings and sealants can be applied to wood flooring in “pre-finishing” that occurs at the manufacturing facility, or onsite. |
|---------------|--|

3 INTRODUCTION TO WARM METHODOLOGY

3.1 A STREAMLINED LIFE-CYCLE INVENTORY

Source reduction, recycling, composting, combustion and landfilling are all materials management options that provide opportunities for reducing GHG emissions, depending on individual circumstances. Although source reduction and recycling are often the most advantageous practices from a GHG perspective, a material-specific comparison of all available materials management options clarifies where the greatest GHG benefits can be obtained for particular materials. A material-specific comparison can help waste managers and policy-makers identify the best options for GHG reductions through materials management.

EPA determined that the best way to conduct such a comparative analysis is a streamlined application of a life-cycle assessment (LCA). A full LCA is an analytical framework for understanding the material inputs, energy inputs and environmental releases associated with manufacturing, using, transporting and disposing of a given material. A full LCA generally consists of four parts: (1) goal definition and scoping; (2) an inventory of the materials and energy used during all stages in the life of a product or process, and an inventory of environmental releases throughout the product life cycle; (3) an impact assessment that examines potential and actual human health effects related to the use of resources and environmental releases; and (4) an assessment of the change that is needed to bring about environmental improvements in the product or processes.

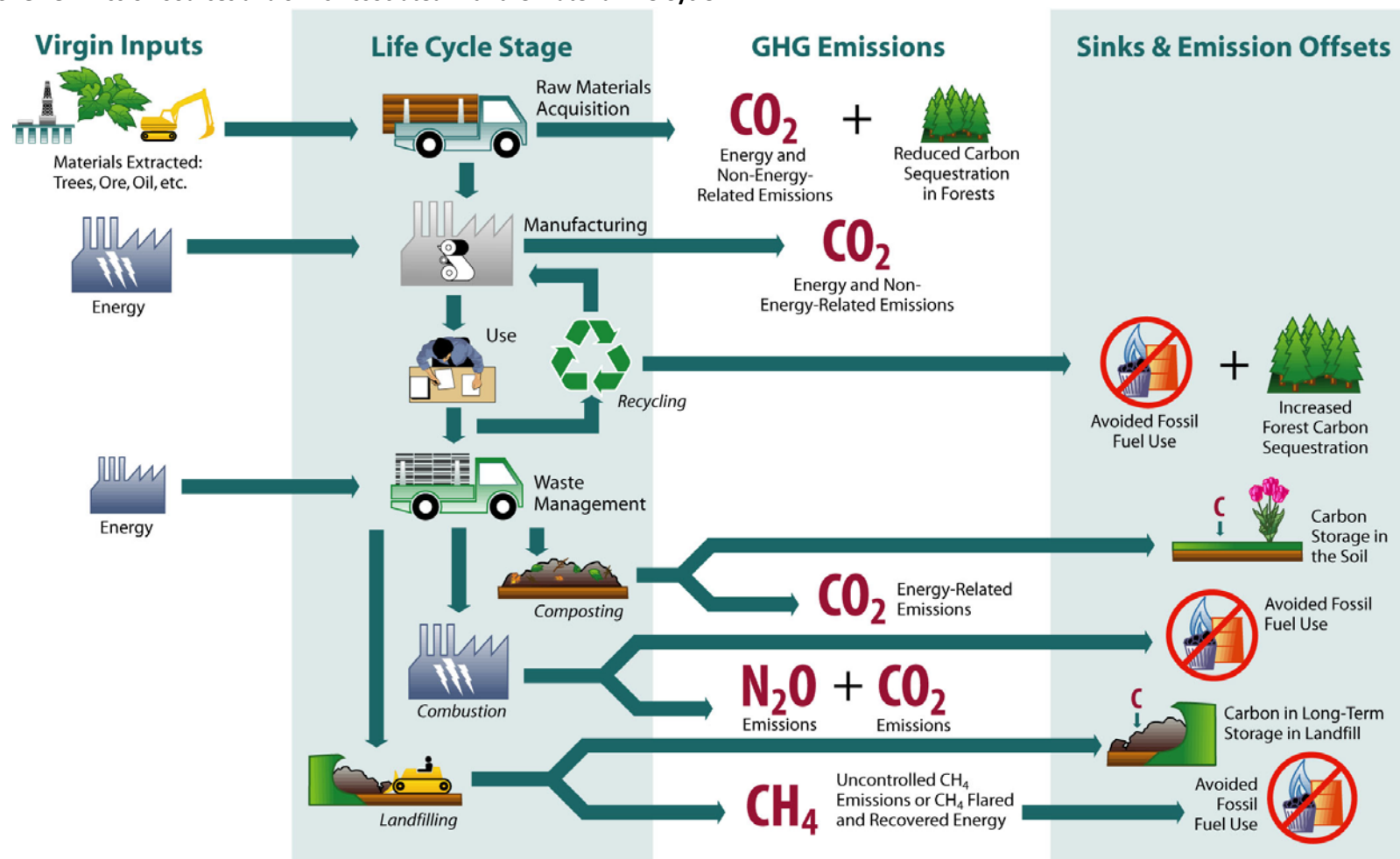
WARM does not provide a full LCA, as EPA wanted the tool to be transparent, easy to access and use, and focused on providing decision-makers with information on climate change impacts, namely GHG and energy implications. WARM’s streamlined LCA is limited to an inventory of GHG emissions and sinks and energy impacts. This study did not assess human health impacts, or air, water or other environmental impacts that do not have a direct bearing on climate change. WARM also simplifies the calculation of emissions from points in the life cycle that occur before a material reaches end of life.

3.2 ASSESSING GHG FLUX ASSOCIATED WITH MATERIAL LIFE-CYCLE STAGES

The streamlined LCA used in WARM depends on accurately assessing the GHG and energy implications of relevant life-cycle stages. The GHG implications associated with materials differ depending on raw material extraction requirements and how the materials are manufactured and disposed of at end of life. WARM evaluates the GHG emissions associated with materials management based on analysis of three main factors: (1) GHG emissions throughout the life cycle of the material (including the chosen end-of-life management option); (2) the extent to which carbon sinks are affected by manufacturing, recycling and disposing of the material; and (3) the extent to which the management option recovers energy that can be used to replace electric utility energy, thus reducing electric utility emissions.

The life cycle of a material or product includes the following primary life-cycle stages: (1) extraction and processing of raw materials; (2) manufacture of products; (3) transportation of materials and products to markets; (4) use by consumers; and (5) end-of-life management. Exhibit 3 shows the GHG sources and carbon sinks associated with the manufacture of various materials and the post-consumer management of these materials as wastes. As shown in the exhibit, GHGs are emitted from (1) the pre-consumer stages of raw materials acquisition and manufacturing, and (2) the post-consumer stage of end-of-life management.

Exhibit 3: GHG Emission Sources and Sinks Associated with the Material Life Cycle



WARM does not include emissions from the use phase of a product's life, since use does not have an effect on the waste management emissions of a product. Since the design and results of WARM include the difference between the baseline and the alternative waste management scenarios that show the GHG savings from different treatment options, emissions from the use phase are the same in both the baseline and alternative scenarios; therefore, emissions from the use phase are excluded and all tables and analyses in this report use a "waste generation" reference point.

Materials management decisions can reduce GHGs by affecting one or more of the following:

- *Energy consumption* (specifically combustion of fossil fuels) and the resulting GHG emissions associated with material extraction, manufacturing, transporting, using, and end-of-life management of the material or product.³
- *Non-energy-related manufacturing emissions*, such as the carbon dioxide (CO₂) released when limestone used in steel manufacturing is converted to lime, or the perfluorocarbons (PFCs) generated during the aluminum smelting process.
- *Methane (CH₄) emissions from decomposition* of organic materials in landfills.
- *CO₂ and nitrous oxide (N₂O) emissions* from waste combustion.
- *Carbon sequestration and storage*, which refer to natural or manmade processes that remove carbon from the *atmosphere and store it* for long periods or permanently.

The first four mechanisms *add* GHGs to the atmosphere and contribute to climate change. The fifth—carbon storage—*reduces* GHG concentrations. Forest growth is one mechanism for sequestering carbon; if more biomass is grown than is removed (through harvest or decay), the amount of carbon stored in trees increases.

Each combination of material or product type and materials management option will have different implications for energy consumption, GHG emissions and carbon storage. This is because the upstream (raw materials acquisition, manufacturing and forest carbon sequestration) and downstream (recycling, composting, combustion and landfilling) characteristics of each material and product are different. Section 3.2 gives an overview of how WARM analyzes each of the upstream and downstream stages in the life cycle. The GHG emissions and carbon sinks are described in detail and quantified for each material in the material-specific chapters.

3.2.1 Waste Generation Reference Point

One important difference between WARM and other life-cycle analyses is that WARM calculates emission impacts from a waste generation reference point, rather than a raw materials extraction reference point. Raw materials extraction is the point at which production of the material begins, which is why many life-cycle analyses choose this reference point. However, WARM uses the waste generation point (the moment that a material is discarded) because in WARM, the GHG benefits measured result from the choice of one waste management path relative to another. WARM does capture upstream emissions and sinks, but only when at least one of the practices being compared is recycling or source reduction, as these are the only instances where the choice of a materials management practice will affect upstream emissions.

³ Depending on the material/product type; however, the use phase is not included in WARM, as discussed in the previous paragraph.

To apply the GHG emission factors developed in this report, one must compare a baseline scenario with an alternate scenario. For example, one could compare a baseline scenario, where 10 tons of office paper are landfilled, to an alternate scenario, where 10 tons of office paper are recycled.

3.3 EMISSIONS SOURCES AND SINKS IN WARM

As discussed above, EPA focused on aspects of the life cycle that have the potential to emit GHGs as materials are converted from raw resources to products and then to waste. Exhibit 4 describes the steps in the material life cycle modeled in WARM at which GHGs are emitted, carbon sequestration is affected, and electric utility energy is displaced. As shown, EPA examined the potential for these effects at the following points in a material's life cycle:

- Raw material acquisition and manufacturing (fossil fuel energy and other emissions, and changes in forest carbon sequestration);
- Carbon sinks in forests and soils (forest carbon storage associated with reduced tree harvest from source reduction and recycling, soil carbon storage associated with application of compost); and
- End-of-life management (CO₂ emissions associated with composting, nonbiogenic CO₂ and N₂O emissions from combustion, and CH₄ emissions from landfills); these emissions are offset to some degree by carbon storage in soil and landfills, as well as by avoided utility emissions from energy recovery at combustors and landfills.
- At each point in the material life cycle, EPA also considered transportation-related energy emissions.

Estimates of GHG emissions associated with electricity used in the raw materials acquisition and manufacturing steps are based on the nation's current mix of energy sources, including fossil fuels, hydropower and nuclear power. However, when estimating GHG emission reductions attributable to electric utility emissions avoided from landfill gas capture or waste-to-energy at combustion facilities, the electricity use displaced by waste management practices is assumed to be from non-baseload power plants to represent the marginal electricity emissions offset. EPA did not analyze the GHG emissions typically associated with consumer use of products because the purpose of the analysis is to evaluate one materials management option relative to another. EPA assumed that the energy consumed during use would be approximately the same whether the product was made from virgin or recycled inputs. In addition, energy use at this life-cycle stage is small (or zero) for all materials studied except personal computers.

Exhibit 4 shows how GHG sources and sinks are affected by each waste management strategy. For example, the top row of the exhibit shows that source reduction (1) reduces GHG emissions from raw materials acquisition and manufacturing; (2) results in an increase in forest carbon sequestration for certain materials; and (3) does not result in GHG emissions from waste management.⁴ The sum of emissions (and sinks) across all steps in the life cycle represents net emissions for each material management strategy.

⁴ The source reduction techniques the EPA researchers analyzed involve using less of a given product—e.g., by making aluminum cans with less aluminum ("lightweighting"); double-sided rather than single-sided photocopying; or reuse of a product. EPA did not analyze source reduction through material substitution (except in the special case of fly ash)—e.g., substituting plastic boxes for corrugated paper boxes. For a discussion of source reduction with material substitution, see the [Source Reduction](#) chapter.

Exhibit 4: Components of Net Emissions for Various Materials Management Strategies

| Materials Management Strategies | GHG Sources and Sinks Modeled in WARM | | |
|---------------------------------|---|--|--|
| | Raw Materials Acquisition and Manufacturing | Changes in Forest or Soil Carbon Storage | End of Life |
| Source Reduction | Offsets <ul style="list-style-type: none"> Decrease in GHG emissions, relative to the baseline of manufacturing with the current industry average mix of virgin and recycled inputs | Offsets <ul style="list-style-type: none"> Increase in forest carbon sequestration (for paper and wood products) due to avoided harvesting | NA |
| Recycling | Emissions <ul style="list-style-type: none"> Transport of recycled materials Recycled manufacture process energy and non-energy Offsets <ul style="list-style-type: none"> Transport of raw materials and products Virgin manufacture process energy and non-energy | | Emissions <ul style="list-style-type: none"> Transport to recycling facility and sorting of recycled materials at material recovery facility (MRF) |
| Composting ^a | NA ^b | Offsets <ul style="list-style-type: none"> Increase in soil carbon storage from application of compost to soils | Emissions <ul style="list-style-type: none"> Transport to compost facility Equipment use at compost facility |
| Combustion | Emissions <ul style="list-style-type: none"> Baseline process and transportation emissions due to manufacture with the current mix of virgin and recycled inputs | NA | Emissions <ul style="list-style-type: none"> Transport to WTE facility Combustion-related non-biogenic CO₂ and N₂O Offsets <ul style="list-style-type: none"> Avoided electric utility emissions due to WTE Avoided steel manufacture from steel recovery at WTE for combusted materials including steel cans, mixed metals, mixed recyclables, PCs, tires and mixed MSW |
| Landfilling | Emissions <ul style="list-style-type: none"> Baseline process and transportation emissions due to manufacture with the current mix of virgin and recycled inputs | NA | Emissions <ul style="list-style-type: none"> Transport to landfill Equipment use at landfill Landfill methane Offsets <ul style="list-style-type: none"> Avoided utility emissions due to landfill gas to energy Landfill carbon storage |

NA = Not Applicable.

^a Includes composting of food scraps and yard trimmings.^b No manufacturing transportation GHG emissions are considered for composting of food scraps and yard trimmings because these materials are not considered to be manufactured.

CO₂ Emissions from Biogenic Sources

The United States and all other parties to the United Nations Framework Convention on Climate Change (UNFCCC) agreed to develop inventories of GHGs for purposes of (1) developing mitigation strategies and (2) monitoring the progress of those strategies. In 2006, the Intergovernmental Panel on Climate change (IPCC) updated a set of inventory methods that it had first developed in 1996 to be used as the international standard (IPCC (1996); IPCC (2006)). The methodologies used in this report to evaluate emissions and sinks of GHGs are consistent with the IPCC guidance.

One of the elements of the IPCC guidance that deserves special mention is the approach used to address CO₂ emissions from biogenic sources. For many countries, the treatment of CO₂ flux from biogenic sources is most important when addressing releases from energy derived from biomass (e.g., burning wood), but this element is also important when evaluating waste management emissions (for example, the decomposition or combustion of grass clippings or paper). The carbon in paper and grass trimmings was originally removed from the atmosphere by photosynthesis and, under natural conditions, it would cycle back to the atmosphere eventually as CO₂ due to degradation processes. The quantity of carbon that these natural processes cycle through the Earth's atmosphere, waters, soils and biota is much greater than the quantity added by anthropogenic GHG sources. But the focus of the UNFCCC is on anthropogenic emissions—those resulting from human activities and subject to human control. Those emissions have the potential to alter the climate by disrupting the natural balances in carbon's biogeochemical cycle and altering the atmosphere's heat-trapping ability.

For processes with CO₂ emissions, if the emissions are from biogenic materials and the materials are grown on a sustainable basis, then those emissions are considered simply to close the loop in the natural carbon cycle. They return to the atmosphere CO₂ that was originally removed by photosynthesis. In this case, the CO₂ emissions are *not* counted. (For purposes of this analysis, biogenic materials are paper and wood products, yard trimmings and food discards.) On the other hand, CO₂ emissions from burning fossil fuels *are* counted because these emissions would not enter the cycle were it not for human activity. Likewise, CH₄ emissions from landfills *are* counted. Even though the source of carbon is primarily biogenic, CH₄ would not be emitted were it not for the human activity of landfilling the waste, which creates anaerobic conditions conducive to CH₄ formation.

Note that this approach does not distinguish between the timing of CO₂ emissions, provided that they occur in a reasonably short time scale relative to the speed of the processes that affect global climate change. In other words, as long as the biogenic carbon would eventually be released as CO₂, whether it is released virtually instantaneously (e.g., from combustion) or over a period of a few decades (e.g., decomposition on the forest floor) is inconsequential.

4 SUMMARY OF THE LIFE-CYCLE STAGES MODELED IN WARM

4.1 GHG EMISSIONS AND CARBON SINKS ASSOCIATED WITH RAW MATERIALS ACQUISITION AND MANUFACTURING

Raw inputs are needed to make various materials, including ore for manufacturing metal products, trees for making paper products, and petroleum or natural gas for producing plastic products. Fuel energy also is required to obtain or extract these material inputs. The top left corner of the Exhibit 3 material life cycle figure shows inputs for *raw materials acquisition*.

The inputs for *manufacturing* considered in this analysis are (1) energy and (2) either virgin raw materials or recycled materials.⁵ In the exhibit, these inputs are identified with arrows that point to the icon labeled “Manufacturing.”

When a material is source reduced, GHG emissions associated with raw material acquisition, producing the material and/or manufacturing the product and managing the post-consumer waste are avoided. Since many materials are manufactured from a mix of virgin and recycled inputs, the quantity of virgin material production that is avoided is not always equal to the quantity of material source reduced. To estimate GHG emissions associated with source reduction, WARM uses a mix of virgin and recycled inputs (referred to throughout the documentation as “the current mix”), based on the national average for that material. For example, in source reducing 100 tons of aluminum cans, WARM models that only 32 tons of virgin aluminum manufacture are avoided, because the current mix for aluminum is 32 percent virgin inputs and 68 percent recycled inputs. WARM also assumes that source reduction of paper and wood products increases the amount of carbon stored in forests by reducing the amount of wood harvested. See the Source Reduction process chapter for further information on calculation of offsets resulting from source reduction.

The GHG emissions associated with raw materials acquisition and manufacturing are (1) GHG emissions from energy used during the acquisition and manufacturing processes, (2) GHG emissions from energy used to transport materials, and (3) non-energy GHG emissions resulting from manufacturing processes.⁶ Each of these emission sources is described below. Changes in carbon sequestration in forests also are associated with raw materials acquisition for paper and wood products. For more information on forest carbon sequestration associated with source reduction of paper and wood products, see the Forest Carbon Storage chapter.

4.1.1 Process Energy GHG Emissions

Process energy GHG emissions consist primarily of CO₂ emissions from the combustion of fuels used in raw materials acquisition and manufacturing. CO₂ emissions from combustion of biomass are not counted as GHG emissions. (See “CO₂ Emissions from Biogenic Sources” text box in section 3.3.)

The majority of process energy CO₂ emissions result from the direct combustion of fuels, e.g., to operate ore mining equipment or to fuel a blast furnace. Fuel also is needed to extract the oil or mine the coal that is ultimately used to produce energy and transport fuels to the place where they are used. Thus, indirect CO₂ emissions from “precombustion energy” are counted in this category as well. When electricity generated by combustion of fossil fuels is used in manufacturing, the resulting CO₂ emissions are also counted.

To estimate process energy GHG emissions, EPA first obtained estimates of both the total amount of process energy used per ton of product (measured in British thermal units or Btu) and the fuel mix (e.g., diesel oil, natural gas, fuel oil). Next, emission factors for each type of fuel were used to convert fuel consumption to GHG emissions based on fuel combustion carbon coefficients per fuel type (EPA, 2011). As noted earlier, making a material from recycled inputs generally requires less process energy (and uses a different fuel mix) than making the material from virgin inputs.

⁵ Water is also often a key input to manufacturing processes, but is not considered here because it does not have direct GHG implications.

⁶ For some materials (plastics, magazines/third-class mail, office paper, phone books, and textbooks), the transportation data EPA received were included in the process energy data. For these materials, EPA reports *total* GHG emissions associated with process and transportation in the “process energy” estimate. The transportation energy estimate therefore only includes emissions from transport from the point of manufacture to a retail facility.

The fuel mixes used in these calculations reflect the material-specific industry average U.S. fuel mixes for each manufacturing process. However, it is worth noting that U.S. consumer products (which eventually become MSW) increasingly come from overseas, where the fuel mixes may differ. For example, China relies heavily on coal and generally uses energy less efficiently than does the United States. Consequently the GHG emissions associated with the manufacture of a material in China may be higher than they would be for the same material made in this country. In addition, greater energy is likely to be expended on transportation to China than on transportation associated with domestic recycling. However, such analysis is beyond the scope of this model, which focuses only on domestic production, transportation, consumption and disposal.

4.1.2 Process Non-Energy GHG Emissions

Some GHG emissions occur during the manufacture of certain materials and are not associated with energy consumption. In this analysis, these emissions are referred to as *process non-energy emissions*. For example, the production of steel or aluminum requires lime (calcium oxide, or CaO), which is produced from limestone (calcium carbonate, or CaCO₃), and the manufacture of lime results in CO₂ emissions. In some cases, process non-energy GHG emissions are associated only with production using virgin inputs; in other cases, these emissions result when either virgin or recycled inputs are used.

4.1.3 Transportation Energy GHG Emissions

Transportation energy GHG emissions consist of CO₂ emissions from the combustion of fossil fuels used to (1) transport raw materials and intermediate products during the manufacturing stage and (2) transport the finished products from the manufacturing facilities to the retail/distribution point.

The estimates of transportation energy emissions for transportation of raw materials to the manufacturing or fabrication facility are based on: (1) the amounts of raw material inputs and intermediate products used in manufacturing one short ton of each material; (2) the average distance that each raw material input or intermediate product is transported; and (3) the transportation modes and fuels used. For the amounts of fuel used, the study used data on the average fuel consumption per ton-mile for each mode of transportation as represented in the industry average life-cycle inventory data.

The estimates of GHG emissions from transporting manufactured products or materials from the manufacturing point to the retail/distribution point are calculated using information from the U.S. Census Bureau, along with the Bureau of Transportation Statistics. These agencies conducted a Commodity Flow Survey that determined the average distance typical commodities were shipped in the United States, and the percentage of each of the various transportation modes that was used to ship these commodities (U.S. Census Bureau, 2003). However, there is large variability in the shipping distance and modes used, and so transportation emission estimates given here are somewhat uncertain.

The final step of the analysis applies fuel combustion carbon coefficients for each fuel type from the U.S. Inventory in order to convert fuel consumption to GHG emissions (EPA, 2011).

4.1.4 Carbon Storage, Carbon Sequestration and Carbon Stocks

This analysis includes carbon sequestration and storage when relevant to materials management practices. Carbon storage is the prevention of the release of carbon to the atmosphere. In the context of WARM, this storage can occur in living trees, in undecomposed biogenic organic matter (wood, paper, yard trimmings, food scraps) in landfills, or in undecomposed biogenic organic matter in soils due to compost amendment.

Carbon sequestration is the transfer of carbon from the atmosphere to a carbon pool, where it can be stored if it is not rereleased to the atmosphere through decay or burning. Carbon sequestration occurs when trees or other plants undergo photosynthesis, converting CO₂ in the atmosphere to carbon in their biomass. As forests grow, they absorb atmospheric CO₂ and store it. When the rate of uptake exceeds the rate of release, carbon is said to be sequestered. In this analysis, EPA considers the impact of waste management on forest carbon storage. The amount of carbon stored in forest trees is referred to as a forest's carbon stock. WARM models carbon storage, sequestration and stocks at several points in the life-cycle analysis, as detailed below:

- Forest carbon storage *increases* as a result of source reduction or recycling of paper products because both source reduction and recycling cause annual tree harvests to drop below otherwise anticipated levels (resulting in additional accumulation of carbon in forests). Consequently, source reduction and recycling “get credit” for increasing the forest carbon stock, whereas other waste management options (combustion and landfilling) do not. See the [Source Reduction](#) and [Recycling](#) process chapters for more information on this modeling analysis.
- Although source reduction and recycling are associated with forest carbon storage, the application of compost to degraded soils enhances soil carbon storage. The [Composting](#) process chapter details the modeling approach used to estimate the magnitude of carbon storage associated with composting.
- Landfill carbon stocks increase over time because much of the organic matter placed in landfills does not decompose, especially if the landfill is located in an arid area. See the [Landfilling](#) process chapter for further information on carbon storage in landfills.

4.2 GHG EMISSIONS AND CARBON SINKS ASSOCIATED WITH MATERIALS MANAGEMENT

As shown in Exhibit 4, depending on the material, WARM models up to four post-consumer materials management options, including recycling, composting, combustion and landfilling. WARM also models source reduction as an alternative materials management option. This section describes the GHG emissions and carbon sinks associated with each option.

4.2.1 Recycling

When a material is recycled, this analysis assumes that the recycled material replaces the use of virgin inputs in the manufacturing process. This approach is based on the assumption that demand for new materials/products and demand for recycled materials remains constant. In other words, increased recycling does not cause more (or less) material to be manufactured than would have otherwise been produced. In WARM, each ton of recycled material would displace the virgin material that would have been produced in the absence of recycling. EPA recognizes that, in reality, there may be a relationship between recycling and demand for products with recycled content since these products may become cheaper as the supply of recycled materials increases. However, for the purpose of simplicity in WARM, EPA assumed that increased recycling does not change overall demand for products.

The avoided GHG emissions from remanufacture using recycled inputs is calculated as the difference between (1) the GHG emissions from manufacturing a material with 100 percent recycled inputs, and (2) the GHG emissions from manufacturing an equivalent amount of the material (accounting for loss rates associated with curbside collection losses and remanufacturing losses) with 100 percent virgin inputs. The GHG emissions associated with manufacturing a material with 100 percent recycled inputs includes the process of collecting and transporting the recyclables used in remanufacture. EPA did not consider GHG emissions at the MSW management stage because the

recycled material is diverted from waste management facilities (i.e., landfills or combustion facilities).⁷ If the product made from the recycled material is later composted, combusted or landfilled, the GHG emissions at that point would be attributed to the product that was made from the recycled material. The [Recycling](#) chapter discusses the process in further detail.

Recycling processes can be broadly classified into two different categories: open-loop and closed-loop recycling. Most of the materials in WARM are modeled in a closed-loop recycling process where end-of-life products are recycled back into the same product (e.g., a recycled aluminum can becomes a new aluminum can). Decisions about whether to model materials in an open-loop or closed-loop process are based on how the material is most often recycled and the availability of data. For materials recycled in an open loop, the products of the recycling process differ from the inputs. In open-loop emission factors, the GHG benefits of material recycling result from the avoided emissions associated with the virgin manufacture of the *secondary* products into which the material is recycled.

The materials modeled as open-loop recycling processes in WARM are: [mixed paper](#), [corrugated containers](#) (partial open-loop) [copper wire](#), [carpet](#), [personal computers](#), [concrete](#), [tires](#), [fly ash](#), [asphalt shingles](#) and [drywall](#) (partial open-loop).^{8, 9} For more detail on the recycling pathways for particular materials or products, see the material-specific chapter. For more information on recycling, see the [Recycling](#) process chapter.

4.2.2 Source Reduction

In this analysis, source reduction is measured by the amount of material that would otherwise be produced but is not generated due to a program promoting waste minimization or source reduction. [Source Reduction](#) refers to any change in the design, manufacture, purchase or use of materials or products (including packaging) that reduces the amount of material entering the waste collection and disposal system. Source reduction conserves resources and reduces GHG emissions. The avoided GHG emissions are based on raw material acquisition and manufacturing processes for the industry average current mix of virgin and recycled inputs for materials in the marketplace.¹⁰ There are no emissions from end-of-life management because it is assumed that a certain amount of material or product was never produced in the first place.

4.2.3 Composting

WARM models composting as resulting in both carbon storage and minimal CO₂ emissions from transportation and mechanical turning of the compost piles. Composting also results in CO₂ emissions from the decomposition of source materials, which include leaves, brush, grass, food waste and newspaper. However, as described in the text box on “CO₂ Emissions from Biogenic Sources,” the biogenic CO₂ emitted from these materials during composting is not counted toward GHG emissions. Composting does result in increased soil carbon storage due to the effects of compost application on soil

⁷ The EPA researchers did not include GHG emissions from managing residues (e.g., wastewater treatment sludges) from the manufacturing process for either virgin or recycled inputs.

⁸ Note that corrugated is modeled using a partial open-loop recycling process. Roughly 70 percent of the recycled corrugated is closed-loop (i.e., replaces virgin corrugated) and 30 percent is open-loop (i.e., replaces boxboard).

⁹ Most recycled drywall is used for a variety of agricultural purposes, but can also be recycled back into new drywall. Approximately 20 percent of recycled drywall is closed-loop (i.e., replaces virgin drywall) and 80 percent is open-loop (i.e., used for agricultural purposes).

¹⁰ Changes in the mix of production (i.e., higher proportions of either virgin or recycled inputs) result in incremental emissions (or reductions) with respect to this reference point.

carbon restoration and humus formation. For more information on GHG flux resulting from composting, see the [Composting](#) process chapter.

Composting may result in some production of CH₄ (due to anaerobic decomposition during composting), but WARM currently assumes that the CH₄ oxidizes to CO₂ before it escapes from the compost pile. However, there is evidence of detectable CH₄ and N₂O emissions from the surface of compost heaps, and research to quantify and assess these emissions is ongoing.

4.2.4 Combustion

When materials are combusted at waste-to-energy facilities, GHGs in the form of CO₂ and N₂O are emitted. Nonbiogenic CO₂ emitted during combustion (i.e., CO₂ from plastics) is counted toward the GHG emissions associated with combustion, but biogenic CO₂ (i.e., CO₂ from paper products) is not. WARM assumes that the combustion pathway involves only waste-to-energy facilities that produce electricity. This electricity substitutes for utility-generated electricity and therefore the net GHG emissions are calculated by subtracting the electric utility GHG emissions avoided from the gross GHG emissions. GHG emissions from combustion are described further in the [Combustion](#) chapter.

4.2.5 Landfilling

When organic matter is landfilled, some of this matter decomposes anaerobically and releases CH₄. Some of the organic matter never decomposes at all; instead, the carbon becomes stored in the landfill. Landfilling of metals and plastics does not result in CH₄ emissions or carbon storage.

At some landfills, virtually all of the CH₄ produced is released to the atmosphere. At others, CH₄ is captured for flaring or combustion with energy recovery (e.g., electricity production). Almost all of the captured CH₄ is converted to CO₂, but is not counted in this study as a GHG because it is biogenic. With combustion of CH₄ for energy recovery, emission factors reflect the electric utility GHG emissions avoided. Regardless of the fate of the CH₄, the landfill carbon storage associated with landfilling of some organic materials is accounted for. GHG emissions and carbon sinks from landfilling are described in the [Landfilling](#) chapter.

4.2.1 Forest Carbon Storage

See section 4.1.4 for discussion.

4.2.2 Avoided Electric Utility GHG Emissions Related to Waste

Waste that is used to generate electricity (either through waste combustion or recovery and burning of CH₄ from landfills) displaces fossil fuels that utilities would otherwise use to produce electricity. Fossil fuel combustion is the single largest source of GHG emissions in the United States. When waste is substituted for fossil fuels to generate electricity, the GHG emissions from burning the waste are offset by the avoided electric utility GHG emissions. When gas generated from decomposing waste at a landfill is combusted for energy, GHG emissions are reduced from the landfill itself, and from avoided fossil fuel use for energy.

4.3 TEMPORAL ASPECTS OF EMISSION FACTORS IN WARM

The emission factors used by WARM represent the full life-cycle changes in GHG emissions resulting from an alternative end-of-life management practice relative to the current, or baseline practice. Certain components of these life-cycle GHG emission factors, however, do not occur immediately following end-of-life management of a material, but over a longer period of time. For example, for paper, yard waste and food waste materials, not all of the GHG reductions occur within the same year of recycling; a portion of the reduction in GHG emissions results from avoided methane

emissions from landfills and increased carbon storage in soils and forests. These emission reductions, resulting from the avoided degradation of organic materials into methane in landfills and the accumulation of carbon in forests, can occur over a timeframe of years to decades.

Consequently, WARM correctly accounts for the full range of GHG emission benefits from alternative waste management practices, but it does not explicitly model the timing of GHG reductions from these practices. Therefore, since WARM is a tool that describes the full life-cycle benefits of alternative waste management pathways, it is not appropriate to directly compare the benefits of alternative waste management as modeled through WARM with traditional GHG Inventory reports, which quantify GHG emissions from different sectors on an annual basis. This section explains the temporal components of WARM's emission factors, and explains how WARM considers these timing issues.

4.3.1 Temporal Components of WARM

The GHG emissions that occur throughout a materials management pathway can be released instantaneously or over a period of time. For example, while combustion instantaneously releases GHGs, the energy used to transport materials releases GHGs over the course of the trip, and materials decomposing in landfills may release methane for decades. Four main parts of the life-cycle GHG emissions and sinks calculated by WARM occur over time: (1) landfill methane emissions, (2) landfill carbon storage, (3) forest carbon sequestration and storage, and (4) soil carbon storage from compost. All four temporal components are relevant to management of organic materials such as paper and other wood products, food scraps and yard trimmings.

- Landfill Methane Emissions: When placed into a landfill, a fraction of the carbon within organic materials degrades into methane emissions. The quantity and timing of methane emissions released from the landfill depends upon at least four factors: (1) how much of the original material decays into methane (varies from material to material), (2) how readily the material decays, (3) landfill moisture conditions (wetter leading to faster decay), and (4) landfill gas collection practices. Food scraps and yard trimmings degrade within 20 to 30 years; materials with slower decay rates, such as paper and lumber types, release a sizable fraction of their ultimate methane emissions after 30 years.
- Landfill Carbon Storage: The fraction of carbon in organic materials that does not degrade into landfill gas is permanently stored in the landfill. Consequently, the amount of carbon stored in the landfill over time is affected by how much of the original material decays into landfill gas, and the speed (or rate) at which the material decays.
- Forest Carbon Sequestration and Storage: Recycling or "source reducing" wood products offsets the demand for virgin wood. Trees that would otherwise be harvested are left standing in forests. In the short term, this reduction in harvest increases carbon storage in forests; over the longer-term, some of this additional carbon storage decreases as forest managers adjust by planting fewer new trees in managed forests. Results from USDA Forest Service models suggest that the forest carbon storage benefit is long-term, lasting at least for several decades (EPA, 2006, p. 41). WARM's life-cycle perspective includes several timing issues involving complex economic relationships that affect the market for wood products (e.g., change in demand for virgin wood, adjustment in harvest practices and change in forest management in response to tree harvesting) relevant to carbon storage and release.
- Soil Carbon Storage: The stock of carbon in soils is the result of a balance between inputs (usually plant matter) and outputs (primarily CO₂ flux during decomposition of organic matter).

When compost is applied to soils, a portion of the carbon in the compost remains undecomposed for many years and acts as a carbon sink. While research into the mechanisms and magnitude of carbon storage is ongoing by EPA, WARM currently assumes that carbon from compost remains stored in the soil through two main mechanisms: direct storage of carbon in depleted soils and carbon stored in non-reactive humus compounds. Although the carbon storage rate declines with time after initial application, the life-cycle perspective in WARM assumes that the carbon stored in compost after a 10-year period is stable in the long term.

Evaluating the timing of GHG emissions from waste management practices involves a high level of uncertainty. For example, the timing of methane emissions from and carbon storage in landfills depends upon uncertain and variable parameters such as the ultimate methane yield and rate of decay in landfills; evaluating forest carbon storage involves complex economic relationships that affect the market for wood products and the management of sustainably harvested forests. In addition to the four components described above, timing issues may also apply to process energy and non-energy emissions from raw material acquisition and manufacturing, transportation and other activities. Timing issues for these components could depend upon factors such as how quickly markets respond to changes in demand for virgin materials given increases in recycling.

EPA designed WARM as a tool for waste managers to use to compare the full, life-cycle GHG benefits of alternative waste management pathways. Its strength as a tool is due to the relatively simple framework that distills complicated analyses of the life-cycle energy and GHG emissions implications of managing materials into a user-friendly spreadsheet model. The purpose of WARM, therefore, is to capture the full life-cycle benefits of alternative waste management practices rather than model the timing of GHG emissions or reductions.

This is fundamentally different from GHG inventories that quantify GHG emissions from different sectors on an annual basis. GHG inventories, in contrast, are used to establish baselines, track GHG emissions and measure reductions over time. The annual perspective of inventories, however, changes depending upon the timeframe used to evaluate GHG emissions, offering a narrow—and sometimes incomplete—picture of the full life-cycle benefits of materials management options. In contrast, the life-cycle view is exactly the perspective that WARM is designed to communicate. As a result, WARM's emission factors cannot be applied to evaluate reductions from annual GHG inventories because they do not necessarily represent annual reductions in emissions (i.e., emission reductions that occur within the same calendar year).

5 LIMITATIONS

When conducting this analysis, EPA used a number of analytical approaches and numerous data sources, each with its own limitations. In addition, EPA made and applied assumptions throughout the analysis. Although these limitations would be troublesome if used in the context of a regulatory framework, EPA believes that the results are sufficiently accurate to support their use in decision-making and voluntary programs. Some of the major limitations include the following:

- The manufacturing GHG analysis is based on estimated industry averages for energy usage, and in some cases the estimates are based on limited data. In addition, EPA used values for the average GHG emissions per ton of material produced, not the marginal emission rates per incremental ton produced. In some cases, the marginal emission rates may be significantly different.

- The forest carbon sequestration analysis deals with a very complicated set of interrelated ecological and economic processes. Although the models used represent the state-of-the-art in forest resource planning, their geographic scope is limited. Because of the global market for forest products, the actual effects of paper recycling would occur not only in the United States but in Canada and other countries. Other important limitations include: (1) the model assumes that no forested lands will be converted to non-forest uses as a result of increased paper recycling; and (2) EPA uses a point estimate for forest carbon sequestration, whereas the system of models predicts changing net sequestration over time. Forest carbon sequestration is discussed further in the Forest Carbon Storage chapter.
- The composting analysis considers a small sampling of feedstocks and a single compost application (i.e., agricultural soil). The analysis did not consider the full range of soil conservation and management practices that could be used in combination with compost and their impacts on carbon storage.
- The combustion analysis uses national average values for several parameters; variability from site to site is not reflected in the estimate.
- The landfill analysis (1) incorporates some uncertainty on CH₄ generation and carbon sequestration for each material type, due to limited data availability; and (2) uses estimated CH₄ recovery levels for the year 2009 as a baseline.
- Every effort has been made to tailor WARM to the conditions found in the United States, including, where possible, production processes, fuel mixes and other underlying factors. Therefore, the results can only be considered applicable to the United States, and caution should be used in applying or extrapolating them to other countries.

EPA cautions that the emission factors in WARM should be evaluated and applied with an appreciation for the limitations in the data and methods, as described further at the end of each chapter.

6 REFERENCES

- Atech Group. (2001). A National Approach to Waste Tyres. Prepared for Environment Australia, June, Table 6.10, p. 34.
- Athena. (2001). A Life Cycle Inventory for Road and Roofing Asphalt. Ottawa: Athena Sustainable Materials Institute.
- Athena Sustainable Materials Institute. (2000). Life Cycle Analysis of Residential Roofing Products. Ottawa.
- Athena Sustainable Materials Institute. (1998). Life Cycle Analysis of Brick and Mortar Products. Merrickville, ON.
- Barlaz, M.A. (1998) Carbon storage during biodegradation of municipal solid waste components in laboratory-scale landfills. *Global Biogeochem. Cycles*, 12 (2), 373–380.
- Battelle. (1975). Energy Use Patterns in Metallurgical and Nonmetallic Mineral Processing (Phase 4—Energy Data and Flowsheets, High-priority Commodities). In U.S. National Technical Information Service (Ed.), U.S. Bureau of Mines Open-File Report 80–75 (pp. 57–59). Columbus, OH: Battelle Columbus Laboratories.

- Bergman, R. (2010). Personal communication between Richard Bergman, USDA Forest Service, and Robert Renz and Christopher Evans, ICF International, March 15, 2010.
- Bergman, R., & Bowe, S. A. (2008). Environmental impact of producing hardwood lumber using life-cycle inventory. *Wood and Fiber Science*, 40 (3), 448–458. Retrieved from <http://www.treesearch.fs.fed.us/pubs/31113>.
- BTS. (2007). US Census Commodity Flow Survey. Table 1: Shipment Characteristics by Mode of Transportation for the United States: 2007. Washington, DC: U.S. Bureau of Transportation Statistics, Research and Innovative Technology Administration. Retrieved from http://www.bts.gov/publications/commodity_flow_survey/preliminary_tables_december_2008/html/table_01.html
- CMRA. (2007). Environmental Issues Associated with Asphalt Shingle Recycling. Gainesville, FL: Innovative Waste Consulting Services, LLC, prepared for the Construction Materials Recycling Association, October. Retrieved from <http://www.p2pays.org/ref/42/41583.pdf>.
- Cochran, K. (2006). Construction and Demolition Debris Recycling: Methods, Markets, and Policy. Gainesville: University of Florida, Environmental Engineering Department.
- Corti, A., & Lombardi, L. (2004). End life tyres: Alternative final disposal processes compared by LCA. *Energy*, 29 (12–15), 2089–2108. doi: 10.1016/j.energy.2004.03.014.
- ECOBILAN. (2001). Eco-profile of high volume commodity phthalate esters (DEHP/DINP/DIDP). La Défense, France: ECOBILAN, prepared for The European Council of Plasticisers and Intermediates (ECPI)
- Ecoinvent Centre. (2008). ecoinvent Database v2.1. Swiss Centre for Life Cycle Inventories. Retrieved February 13, 2009, from <http://www.ecoinvent.ch/>.
- EIA. (2009). 2006 Manufacturing Energy Consumption Survey, Table 3.2: Fuel Consumption, 2006 for Synthetic Rubber. (NAICS 325212.) Energy Information Administration. Retrieved from <http://www.eia.doe.gov/emeu/mecs/mecs2006/2006tables.html>.
- Environment Canada. (2005). Determination of the Impact of Waste Management Activities on Greenhouse Gas Emissions: 2005 Update, Final Report. Report prepared for Environment Canada and Natural Resources Canada by ICF Consulting.
- Enviros Consulting. (2003). Glass Recycling – Life Cycle Carbon Dioxide Emissions. Prepared by Enviro Consulting, Limited for the British Glass Manufacturers Confederation, Public Affairs Committee. November.
- EPA. (2011). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2009. Annex 2. April. (EPA publication no. EPA 430-R-11-005.) U.S. Environmental Protection Agency, Office of Atmospheric Programs. April. Retrieved from: <http://epa.gov/climatechange/emissions/usinventoryreport.html>.
- EPA. (2011). Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2010. Washington, DC: U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response. Retrieved from: http://www.epa.gov/osw/nonhaz/municipal/pubs/2010_MSW_Tables_and_Figures_508.pdf.
- EPA. (2009b). Opportunities to Reduce Greenhouse Gas Emissions through Materials and Land Management Practices. (EPA publication no. 530-R-09-017.) Washington, DC: U.S.

- Environmental Protection Agency, Office of Solid Waste and Emergency Response. Retrieved from http://www.epa.gov/oswer/docs/ghg_land_and_materials_management.pdf
- EPA. (2009c). Sustainable Materials Management: The Road Ahead. (EPA publication no. EPA 530-R-09-009.) Washington, DC: U.S. Environmental Protection Agency. Retrieved from <http://www.epa.gov/osw/inforesources/pubs/vision2.pdf>.
- EPA. (2008). Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2007. Washington, DC: U.S. Environmental Protection Agency. Retrieved from <http://www.epa.gov/epawaste/nonhaz/municipal/msw99.htm>.
- EPA. (2006). Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks. (EPA publication no. EPA 530-R-06-004.) Washington, DC: U.S. Environmental Protection Agency, Office of Solid Waste.
- EPA. (2002). Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks. Washington, DC: U.S. Environmental Protection Agency. Retrieved from <http://www.epa.gov/climatechange/wycd/waste/downloads/greengas.pdf>.
- EPA. (1998). Greenhouse Gas Emissions From Management of Selected Materials in Municipal Solid Waste. Background Document A: A Life Cycle of Process and Transportation Energy for Eight Different Materials. Washington, DC: U.S. Environmental Protection Agency. Retrieved from <http://epa.gov/climatechange/wycd/waste/SWMGHGreport.html>.
- FAL. (2011). Cradle-to-Gate Life Cycle Inventory of Nine Plastic Resins and Two Polyurethane Precursors. Revised Final Report. Prairie Village, KS: Franklin Associates, Ltd.
- FAL. (2002a). Energy and Greenhouse Gas Factors for Nylon Broadloom Residential Carpet. Prairie Village, KS: Franklin Associates, Ltd, prepared for U.S. Environmental Protection Agency, Office of Solid Waste.
- FAL. (2002b). Energy and Greenhouse Gas Factors for Personal Computers. Prairie Village, KS: Franklin Associates, Ltd, prepared for U.S. Environmental Protection Agency, Office of Solid Waste.
- FAL. (1998a). Background Document A. Attachment 1: A Partial Life Cycle Inventory of Process and Transportation Energy for Boxboard and Paper Towels. Prairie Village, KS: Franklin Associates, Ltd, prepared for U.S. Environmental Protection Agency, Office of Solid Waste. Retrieved from http://www.epa.gov/climatechange/wycd/waste/downloads/BackgroundDocumentA_Attachment1.pdf
- FAL. (1998b). A Life Cycle Inventory of Process and Transportation Energy for Eight Different Materials--Background Document A. Prairie Village, KS: Franklin Associates, Ltd, prepared for U.S. Environmental Protection Agency, Office of Solid Waste. Retrieved from <http://www.epa.gov/climatechange/wycd/waste/downloads/BackgroundDocumentA.pdf>
- FAL. (1998c). Report with data developed by FAL on dimensional lumber and medium-density fiberboard.
- FAL. (1994). The Role of Recycling in Integrated Solid Waste Management to the Year 2000. Franklin Associates, Ltd. (Keep America Beautiful, Inc., Stamford, CT) September, pp. 1–16.
- Hubbard, S. S., & Bowe, S. A. (2008). Life-Cycle Inventory of Solid Strip Hardwood Flooring in the Eastern United States. Consortium for Research on Renewable Industrial Materials. Retrieved from <http://www.nwfa.org/uplfiles/whatsNew/Hubbard&BoweFinalCORRIMHardwoodFlooringLCReport08.pdf>

- IPCC. (1996). Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories. Paris, France.
- Kusik, C. L., & Kenahan, C. B. (1978). Energy Use Patterns for Metal Recycling. (Information Circular 8781.) Washington, DC: U.S. Dept. of the Interior, Bureau of Mines.
- Levis, J. W. (2008). A Life-Cycle Analysis of Alternatives for the Management of Waste Hot-Mix Asphalt, Commercial Food Waste, and Construction and Demolition Waste. Raleigh: North Carolina State University.
- Lippiatt, B. (2007). Building for Environmental and Economic Sustainability (BEES). Retrieved from <http://www.bfrl.nist.gov/oea/software/bees/>.
- PE Americas (2010). Life Cycle Impact Assessment of Aluminum Beverage Cans. Prepared by PE Americas for Aluminum Association, Inc. Washington, DC. April 22, 2010.
- NatureWorks, LLC (2010). Renewing Ingeo: End-of-Life Options. NatureWorks LLC Website. Retrieved July, 2010 from: <http://www.natureworkslc.com/the-ingeo-journey/end-of-life-options.aspx>
- Nisbet, M. A., VanGeem, M. G., Gajda, J., & Marceau, M. L. (2000). Environmental Life Cycle Inventory of Portland Cement Concrete. (PCA R&D Serial No. 2137). Skokie, IL: Portland Cement Association.
- NREL. (2009). U.S. Life-Cycle Inventory Database. National Renewable Energy Laboratory. Retrieved September 2009.
- PCA. (2003). U.S. Industry Fact Sheet, 2003 Edition. Portland Cement Association: Skokie, IL.
- Realff, M. (2011a). The WARM Model – Analysis and Suggested Action. September 15, 2011.
- Realff, M. (2011b). "WARM_information_FINAL.xls". Excel spreadsheet with life-cycle data provided to ICF International and EPA on July 12, 2011.
- RPTA (2003). Personal communication between Recycled Paper Trade Association (RPTA) and ICF Consulting]
- RTI. (2004). Unpublished database developed jointly by the Research Triangle Institute (RTI) and U.S. Environmental Protection Agency Office of Research and Development.
- U.S. Census Bureau. (2003). Commodity Flow Survey. U.S. Economic Census. Washington, DC. Retrieved from <http://www.census.gov/prod/ec02/02tcf-usp.pdf>.
- U.S. Census Bureau. (2001). Mining-Subject Series, Product Summary. U.S. Economic Census. Washington, DC. Retrieved from <http://www.census.gov/prod/ec97/97n21s-ps.pdf>
- U.S. Census Bureau. (1997). Fuels and Electric Energy Report. U.S. Economic Census. Washington, DC.
- Venta, G. (1997). Life Cycle Analysis of Gypsum Board and Associated Finishing Products. Ottawa: Athena Sustainable Materials Institute.
- Waste Business Journal. (2009). Construction & Demolition Debris Disposal & Recycling. Waste Market Overview and Outlook 2009.
- Wilburn, D. R., & Goonan, T. G. (1998). Aggregates from Natural and Recycled Sources. (USGS Circular no. 1176.) Washington, DC: U.S. Geological Survey.
- WRAP. (2008). Life Cycle Assessment of Plasterboard. Waste & Resources Action Programme, United Kingdom.